2008

Analysis of Efficiency and Power Factor of Reciprocating Compressor Unit Under Variable-Frequency and Variable-Conditions

Xiongpo Hou
Xi'an Jiaotong University

Zhaolin Gu
Xi'an Jiaotong University

Xiufeng Gao
Xi'an Jiaotong University

Shiyu Feng
Xi'an Jiaotong University

Yun Li
Xi'an Jiaotong University

Analysis of Efficiency and Power Factor of Reciprocating Compressor Unit under Variable-Frequency and Variable-Conditions

Xiongpo Hou[1], Zhaolin Gu[2]*, Xiufeng Gao[1], Shiyu Feng[1], Yun Li[1]

[1] Energy and Power Engineering School of Xi'an Jiaotong University,
Xi'an 710049, P. R. China
Tel & Fax: 86 29 82664928
Email: houxp@mail.xjtu.edu.cn

[2] Human Settlements and Civil Engineering School of Xi'an Jiaotong University,
Xi'an 710049, P. R. China
Tel & Fax: 86 29 82665111
Email : guzhaoln@mail.xjtu.edu.cn

*Indicate Corresponding Author

ABSTRACT

Energy efficiency and power factor were most essential performances for compressor unit driven by inverter-fed motors. The performances were simulated utilizing a parametric linear model under variable-frequency and variable-conditions in this paper. The results showed that, at rated frequency, both the performances would fall down with lighter load; if frequency was reduced from rated, energy efficiency would fall even lower, though power factor rose up slightly. By comparison, at frequencies beyond rated, both the performances would go better. The results also showed, whether at infra- or ultra-frequencies, the motor overload capability was more restricted, so it could only be adopted in light-load conditions. This research could be helpful for optimization and energy saving of reciprocating compressor units running under variable frequencies and variable working conditions.

Keywords: Reciprocating Compressor, Inverter-Fed Motor, Efficiency, Power Factor

1. INTRODUCTION

Nowadays more and more reciprocating compressors were driven by inverter-fed motors to meet newer demands or variable working conditions. So it is necessary to take compressor combined with inverter-fed motor as a systematic unit. In many instances, this combination was advised as a solution for energy saving, but the decision didn't seem to be well-founded. In the unit, power was product of torque and rotating speed. The torque required by reciprocating compressor, was the load of motor and was determined by compressor's sucking and draining pressures. Motor was to answer for torque supply, not torque demander. The speed of the unit relied heavily on the inverter output frequency; the influence of load was little. Any change of either power frequency or working conditions would affect the compressor's power consumption, and this would further impose influence on the performance of driving motor, significantly including its energy efficiency and power factor. The strategy for energy saving should be founded on the understanding of the unit behavior of variable conditions and variable frequency.

2. ANALYSIS OF COMPRESSOR WORKING CHARACTERISTICS

The energy input to a reciprocating compressor would be distributed mainly into two parts: its output, indicated work to compress the working gas and drive gas flow, generally more than 85%; and the remaining, mechanical loss by various friction and lubrication, less than 15%. The indicated work had been given in (Yu, 1997), as shown in Equation (1).

$$P_I = \sum_j P_j = \frac{n}{60}\sum_j N_j = \frac{n}{60}\sum_j \lambda_{vj} V_{hj} p'_{sj} \frac{m_j}{m_j - 1}\left\{\left[\varepsilon_j\left(1+\delta_j\right)\right]^{\frac{m_j-1}{m_j}} - 1\right\} \tag{1}$$

Equation (1) showed that indicated work had a complex relation with thermo conditions (sucking and draining pressure), and had a direct proportion to rotation speed. The mechanical loss was affected by complex factors and couldn't form a sound quantitative description. But it was accessible that mechanical loss approximately be positive proportional to rotation speed from an empirically qualitative analysis. So the whole power consumption of compressor would be positive proportional to its speed, and had a complex relation with sucking and draining pressure.

Take a kind of 5.5kW process compressor for an instance. At rated speed (980 r/min), under different sucking and draining pressure, its power consumption was shown in figure 1. Under a certain draining pressure, the power curve shaped like a hump in the whole range of sucking pressure; if draining pressure fell down, the curve would wholly depressed down. When rotation speed changed, the curve would directly changed in corresponding way, as shown in figure 2.

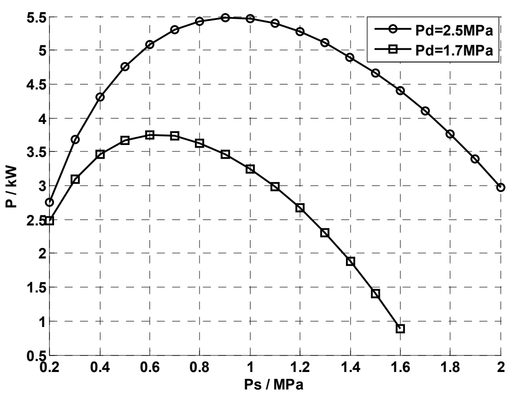

Figure 1. Compressor power vs. pressures
speed=980 r/min(rated 50Hz)

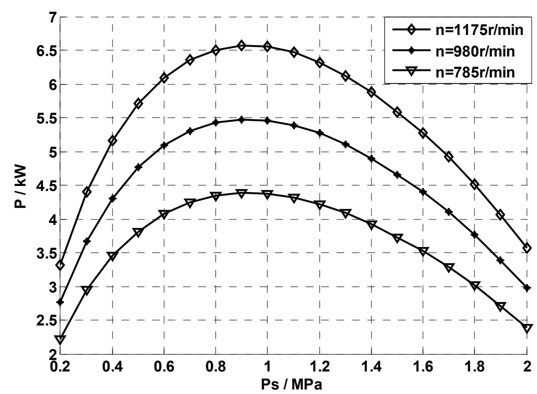

Figure 2. Compressor power at different speed
Pd=2.5MPa

Considering power, torque and speed should comply with Equation (2):

$$P = \frac{T \cdot n}{9550} \tag{2}$$

Thus, when rotation speed changed and thermo-conditions kept standing, the torque would be close to keep constant. This was the same for most types of displacement compressors, but distinct from turbine machines such as fans and pumps.

In general cases, the driving motor should be selected so that it was capable of satisfying the power requirement at the top point of the highest hump encountered in practice. However, this condition could be impossible to appear all the time, and moreover, the gas requirement might change from time to time. So the surplus motor, in most time, was working to waste its talent on a petty job. When the working conditions changed, for energy saving, it was necessary to take measure to make full use of motor capability. When the gas requirement was reduced, the overmuch pressed gas had to be throttled and discharged back to the sucking chamber. For energy saving, it was necessary to reduce the gas supply. So inverter –fed motor came into fashion so that the motor could run at lower speed for lower demand.

3. INVERTER-FED MOTOR PERFORMANCE SIMULATION

3.1 Steady model of Asynchronous induced Motor

The asynchronous induced motor was widely-used converter of electric energy to mechanical energy. The energy input to the motor would also be distributed mainly into two aspects: its output – axial work, generally 90% or so; and the remaining, inside loss, about 10%. The loss would cover up:P_{cu1}, stator loss by current heat on stator windings resistance; P_{Fe1}, excitation loss by on stator magnetic pole; P_{Cu2}, rotor loss by current heat on rotor windings or cage resistance; P_M, Mechanical loss by bearings and fan; andP_{Δ}, all other additional loss. Among above losses, the last item was very slight, 0.5~1% of output power, and could be ignored. For inverter-fed motor, the cooling fan was fed by an independent power to protect the motor in low speed, so the internal mechanical loss was from bearings friction, and it was a bit slight and could be ignored.

(Li and Shi, 1999) introduced an equivalent steady model of asynchronous motor, shown in Figure 3, except that there was no r_m in their original model. The three branches of "T" circuit represented three basic energy components of motor: stator windings, stator magnetic core, and rotor windings. The load on the output axis of rotor was equivalently converted to a changeable analog resistance, $r_2'(1\text{-}s)/s$ .The slip, s, was defined as

$$
\begin{cases}
n_0 = \dfrac{60f}{p} \\
s = \dfrac{n_0 - n}{n_0}
\end{cases}
\tag{3}
$$

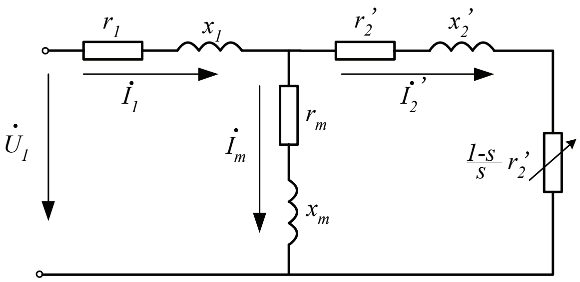

Fig 3. Equivalent steady mode of asynchronous motor

The omission of r_m would result in the neglect of P_{Fe1} in the simulation. Excitation reactance x_m was usually much higher than stator or rotor resistances, thus the excitation current was closely equal to input current at empty load, which was taken for granted to be trivial. But this was groundless. From small to large-scale motors, the input current at empty load had been measured to be 40~50% of that at full load. So P_{Fe1} couldn't be neglected. Distinguished from (Li and Shi, 1999), in the revised model of Figure 3, a resistance r_m was added into excitation branch and connected serially with excitation reactance x_m.

Define

$$
\begin{cases}
z_1 = r_1 + jx_1 \\
z_m = r_m + jx_m \\
z_2' = \dfrac{r_2'}{s} + jx_2' \\
z = z_1 + z_m // z_2'
\end{cases}
\tag{4}
$$

Then, the current was denoted as:

$$\begin{cases} \dot{I}_1 = \dfrac{\dot{U}}{z}; \\ \dot{I}_m = \dot{I}_1 \dfrac{z_2^{'}}{z_m // z_2^{'}} \\ \dot{I}_2^{'} = \dot{I}_1 \dfrac{z_m}{z_m // z_2^{'}} \end{cases} \text{; and their magnitude } \begin{cases} I_1 = \left|\dot{I}_1\right| \\ I_1 = \left|\dot{I}_1\right| \\ I_2^{'} = \left|\dot{I}_2^{'}\right| \end{cases} \tag{5}$$

The input-output relation was:

$$\begin{cases} \cos\varphi = \dfrac{\mathrm{R(z)}}{|\mathrm{z}|} \\ P_1 = 3U_1 I_1 \cos\varphi \\ P_2 = 3I_2^{'2} r_2^{'} \dfrac{1-s}{s} \\ \eta = \dfrac{P_1}{P_2} = \dfrac{U_1 I_1 \cos\varphi}{I_2^{'2} r_2^{'} \dfrac{1-s}{s}} \end{cases} \tag{6}$$

From (2), (3) and (6), the following could be obtained:

$$P_2 = \frac{T \cdot n}{9550} = \frac{T \cdot n_0 (1-s)}{9550} = 3I_2^{'2} r_2^{'} \frac{1-s}{s} / 1000$$

and

$$T = 28.65 \frac{I_2^{'2} r_2^{'}}{s n_0} \tag{7}$$

In Formula (7), $I_2^{'}$ was implicit function of ***s***. So *T* was a unitary function of ***s***. Formula (4) ~ (7) was the linear quantitative description of an asynchronous induced motor. Define load rate, the practical torque over rated torque at rated frequency, as ***k*** :

$$k = \frac{T}{T_N} \tag{8}$$

Given the value of parameters of motor, the main two performances, η (energy efficiency) and $\cos\varphi$ (power factor), would be calculated at various load. Take a certain motor for example. The rated values were measured in practice as:

P_2=5.5kW, U_1=380V, f=50Hz, p=2, n=1475

r_1=1.31Ω, x_1=2.13Ω; r_m=7Ω, x_m=110Ω; $r_2^{'}$=1.13Ω, $x_2^{'}$=3.4Ω

The result was shown in Figure 4. At rated frequency, both the performances would decline with lighter load, especially when load rate less than 60%, the energy efficiency would drop under 90%, the power factor would drop below 0.7.

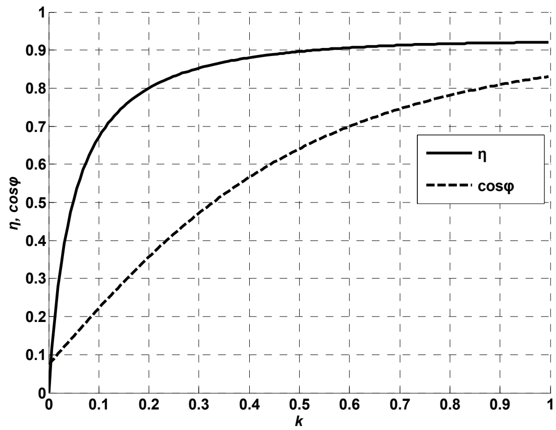

Figure 4. Performances vs. load

3.2 Inverter-fed Motor Simulation

Inverter could change the electric power in frequency and voltage. When frequency was lower than rated, so-called infra-frequency, the frequency would lower, usually proportionally changed. However, when frequency was higher than rated, so-called over-frequency, the voltage could not be raised for the limitation of insulator. As mentioned above, the reciprocating compressor was a kind of constant torque load when its rotation speed varied. Thus however the inverter changed its output frequency, the torque demand by compressor had to be fulfilled.

When supply frequency was changed, the value of parameter in Formula (4) would also changed in proportion:

$$\begin{cases} \alpha = f / f_N \\ x_1 = \alpha x_{1,N} \\ x_m = \alpha x_{m,N} \\ x_2^{'} = \alpha x_{2,N}^{'} \end{cases} \tag{9}$$

Formula (9) ignored the non-sine effect of inverter output waveform, which was venial in modern advanced inverter. Its linearity would be correct up to 100Hz, which was common in usual engineering practice. This change would cause the curve in Figure 4 to shift accordingly.

Assume frequency could be changed from 20Hz to 70Hz. A simulation based on formula (4)~(7) and (9) was applied to the same motor mentioned above, and the results were shown in Figure 5 and 6. It was clear in Figure 5, when the frequency adjusted down from the high, through the rated, and to low value, the efficiency curve would wholly, continuously fall lower and lower. In Figure 6, the power factor curve would be lowest at rated frequency; when frequency changed, whether infra- or over-frequency, the curve would rise up slightly. The results implied that merely making a utilization of inverter could not always result in energy saving. Energy saving should be founded on the optimization of process and operation.

It should be pointed out that, in Figure 5 and 6, the range of load rate, from 0 to 1, was unpractical. When frequency changed, the input current of motor would change also. The input current was another factor to denote the capability of motor to carry the load and was often limited in a certain range by the inverter and upper appliances in electric supply network. Define input current ratio over rated value, ψ**,** as:

$$\psi = I_1 / I_{1,N} \tag{10}$$

An inspection to this change was shown in Figure 7and 8. Figure7 proved that the input current at empty load was about 50% of that at full load. It was also revealed that over-frequency would somehow be helpful to reduce input current when load rate was below 0.5, but it was the other way when load rate beyond 0.5. In Figure 8, whether infra- or over-frequency, the motor capability to carry load and endure overload was weakened. For example, when frequency was 70Hz, the input current would reach the rated value at load rate 0.78; another, when frequency was 20Hz, the input current would reach the rated value at load rate 0.95. This could mean variable frequency could only be adopted in light-load conditions.

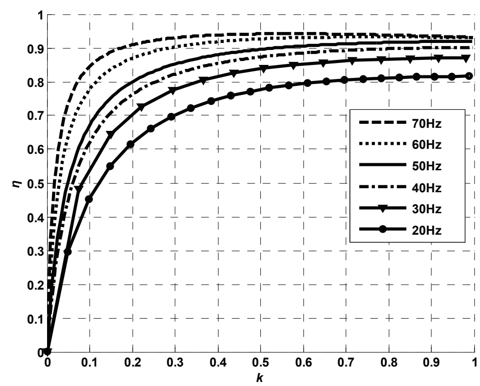

Figure 5. Energy efficiency at different frequencies

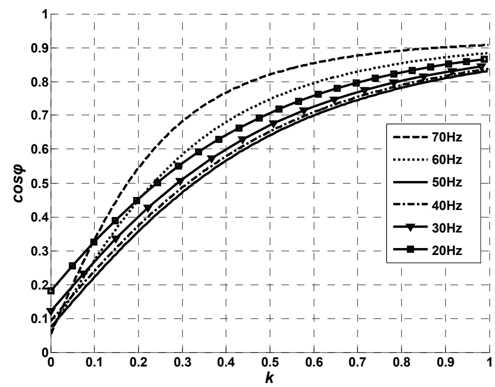

Figure 6. Power factor at different frequencies

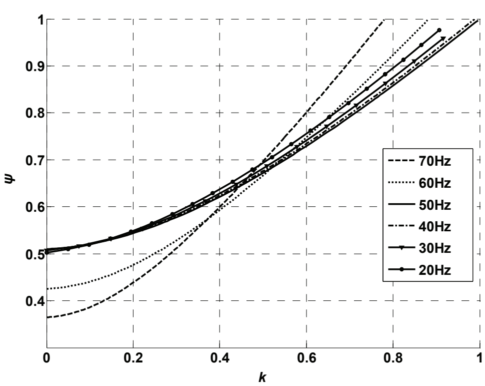

Figure 7. Input Current at different frequencies

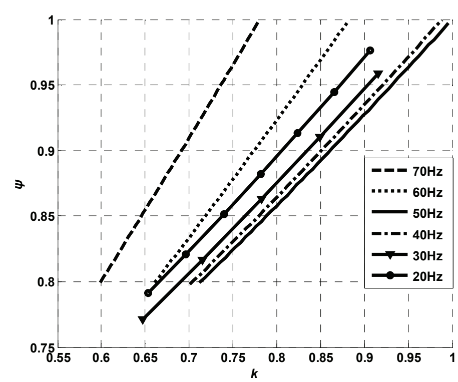

Figure 8. Local detailed of Figure 7

4. CONCLUSIONS

Energy efficiency and power factor were most essential performances for compressor unit driven by inverter-fed motors. The performances were simulated utilizing a parametric linear model under variable-frequency and variable-conditions in this paper.

The results showed that, at rated frequency, both the performances would fall down with lighter load; if frequency was reduced from rated, energy efficiency would fall even lower, though power factor rose up slightly. By comparison, at frequencies beyond rated, both the performances would go better.

The results also showed, whether at infra- or ultra-frequencies, the motor overload capability was more weakened, so it could only be adopted in light-load conditions.

This research could be helpful for optimization and energy saving of reciprocating compressor units running under variable frequencies and variable working conditions.

NOMENCLATURE

P – Power, kW
T —Torque, N·m

n – rotation speed, r/min
N – (subscript) rated value

Compressor:

P_I – indicated work of compressor
j – stages of compressor
P_j – indicated work of each stage;
n – rotation speed; N_j – work in a single cycle of each stage
λ_{vj} – relative dead volume of each stage
V_{hj} – working volume of each stage

m_j – expanding indicator of each stage
ε_j – named pressure ratio of each stage
δ_j –pressure loss of each stage
p'_{sj} – sucking pressure of each stage
Ps – sucking pressure, Mpa
Pd – draining pressure,MPa

Motor:

r_1 – resistance of each stator phase, Ω
x_1 – leak reactance of each stator phase, Ω
r_m – excitation resistance of each stator phase, Ω, according to P_{Fe1}
x_m – excitation reactance of each stator phase, Ω, according to main magnetic flux
r'_2 – converted resistance of each rotor phase, Ω
x'_2 – converted leak reactance of each rotor phase, Ω
$\frac{1-s}{s}r'_2$ – converted variable resistance,
s – slip

f – frequency of power supply, Hz
n_0 – synchronous speed, r/min
$\dot{U}_1$ – voltage of power supply, V
$\dot{I}_1$ – current of each stator phase, A
$\dot{I}_m$ – excitation current of each stator phase, A
$\dot{I}_2$ converted current of each totor phase, A
$\cos\varphi$ – power factor
$\boldsymbol{\eta}$ – energy efficiency
k – load rate
α – frequency ratio
ψ – input current ratio

REFERENCES

Yu, Y. Z., 1997, The Reciprocating Compressors, Xi'an Jiaotong University Press: p.57 (in Chinese)
Li, Y., Shi, W. G., 1999, Research on Running Efficiencies and Energy Saving Control of an Induction Motor Fed by an inverter, ELECTRICAL DRIVE AUTOMATION, Vol. 21, no.1: p.21-25 (in Chinese)

ACKNOWLEDGEMENT

The Authors would like to acknowledge the sponsor of:
the Project of China 863 Program, No.2006AA05Z134; and
the Key Project of China 863 Program, No. 2006AA11A1B8.

The authors were also grateful to Professor Yongzhang Yu, for his contribution to the research.